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Author(s)	Watanabe, Junzo
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THE SYZYGIES OF \underline{m} -FULL IDEALS

北海道東海大学工学部
渡 辺 純 三 (Junzo Watanabe)

Introduction

The concept of \underline{m} -full ideals was introduced and studied first by D.Rees (unpublished). In 1983, after having considered and discussed the concept with Prof. Rees, I went on to show some of their properties in [10]. Some other authors also have obtained a considerable amount of results related to those ideals. (cf. [5], [7].) The purpose of this paper is to seek syzygies of \underline{m} -full ideals and try to analyze their structure. Let \underline{a} be an \underline{m} -full ideal, and \overline{a} the reduction by a general element. Then it is possible to determine the number of basic syzygies of \underline{a} in terms of \overline{a} . As my argument shows, this means that a method can be found for obtaining a set of basic syzygies of \underline{a} provided that that of \overline{a} is known. (Theorem 6.) Moreover the entire structure of the syzygy module is known when it is reduced by a general element. It turns out that $\underline{a}/z\underline{a}$ is the direct sum of \overline{a} and copies of the residue field. (Corollary 7.)

Thus we are naturally lead to define a new class of ideals which we call "completely \underline{m} -full." (Definition 2.) The meaning of this is that they provide us with an inductive set up. For those ideals we may calculate their Betti numbers using certain

numerals $\ell_1, \ell_2, \dots, \ell_n$, as will be shown in Corollary 9.

Finally we relate our results to the theory of Gröbner bases. Several authors have proved that the initial monomials of a Gröbner basis of a homogeneous ideal in a polynomial ring, with respect to generic variables, form a Borel stable ideal. (See [2], [6], [9].) One finds easily that in characteristic 0 a Borel stable ideal is completely \underline{m} -full. Since basic syzygies can be obtained through the reduction process of a Gröbner basis, we have the fact that the Betti numbers of a homogeneous ideal \underline{a} do not exceed those of $\text{in}(\underline{a})$, which is the ideal generated by the initial monomials of a Gröbner basis. When $\text{in}(\underline{a})$ is completely \underline{m} -full, we can apply Theorem 6 to it recursively to express the Betti numbers using the numerals $\ell_1, \ell_2, \dots, \ell_n$. If \underline{a} is \underline{m} -primary, ℓ_1, \dots, ℓ_n are defined and calculated without referring to Gröbner bases. This is stated in Theorem 11.

The basic idea of this paper grew out of many discussions that I had with C.Huneke and W.Heinzer while I was in Purdue University in 1987. I would like to express my thanks to them.

§ 1. Definitions, notation and some examples

Let (R, \underline{m}, k) be a local ring. We use the words "general elements" of R in the sense of D.Rees, which is explained as follows: Let $\underline{m} = (x_1, x_2, \dots, x_n)$. Let y_1, y_2, \dots, y_n be a set of indeterminates and let $z = y_1x_1 + y_2x_2 + \dots + y_nx_n$. Then z is called a general element of R . Strictly speaking, it is an element of $R^* := R(y_1, y_2, \dots, y_n)$, which is the polynomial ring $R[y_1, y_2, \dots, y_n]$ localized at

$\underline{m}R[y_1, y_2, \dots, y_n]$, but, by abuse of language, we treat it as an element of R . For one thing it is easy to pass to R^* without affecting the situation involved, and for another, in most cases it is possible to find in R elements sufficiently general in some sense needed. Sometimes it is necessary for us to choose generators of \underline{m} consisting of general elements. In this case we introduce indeterminates y_{ij} and let $z_i = \sum y_{ij}x_j$ and $\underline{m} = (z_1, z_2, \dots, z_n)$. It should be understood that we either pass to R^* or substitute y_{ij} by suitable elements in R , if they exist, for the particular purpose. We note that a general element is in $\underline{m} \setminus \underline{m}^2$.

Recall that an ideal \underline{a} of a local ring (R, \underline{m}, k) is called \underline{m} -full if there exists an element z such that $\underline{m}\underline{a}:z = \underline{a}$. (Such z may exist only in a faithfully flat extension of R .) Note that $\underline{m}\underline{a}:z = \underline{a}$ for some z implies $\underline{m}\underline{a}:z = \underline{a}$ for a general element z . \underline{m} -Primary \underline{m} -full ideals were treated in [10]. As to non \underline{m} -primary ideals, it should be noted that if $\text{depth } R/\underline{a} > 0$ then \underline{a} is \underline{m} -full. This follows immediately from the general inclusions $\underline{a}:z \supset \underline{m}\underline{a}:z \supset \underline{a}$. Also note that if \underline{a} and \underline{b} are \underline{m} -full then $\underline{a} \cap \underline{b}$ is \underline{m} -full. In fact $\underline{m}(\underline{a} \cap \underline{b}) \subset \underline{m}\underline{a} \cap \underline{m}\underline{b}$. It follows that $\underline{m}(\underline{a} \cap \underline{b}):z \subset (\underline{m}\underline{a} \cap \underline{m}\underline{b}):z = \underline{m}\underline{a}:z \cap \underline{m}\underline{b}:z = \underline{a} \cap \underline{b}$. Now we get $\underline{m}(\underline{a} \cap \underline{b}):z = \underline{a} \cap \underline{b}$, since the other inclusion is obvious. So the intersections of \underline{m} -primary \underline{m} -full ideals with ideals \underline{a} such that $\text{depth } R/\underline{a} > 0$ give us abundant examples of non \underline{m} -primary \underline{m} -full ideals. Here is another example.

EXAMPLE 1. Suppose that $R = k[x_1, x_2, \dots, x_n]$ is the polynomial ring over a field k of characteristic 0. Consider the group of automorphisms of R induced by the linear transformations

$$\begin{cases} x_n \longrightarrow a_1 x_1 + a_2 x_2 + \dots + a_n x_n, & a_n \neq 0, \\ x_i \longrightarrow x_i, & i < n. \end{cases}$$

In the matrix notation, this group corresponds to the following subgroup in $GL(n)$.

$$\left\{ \begin{pmatrix} 1 & 0 & 0 & 0 & \dots & 0 & * \\ 0 & 1 & 0 & 0 & \dots & 0 & * \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & 1 & * \\ 0 & 0 & 0 & \dots & 0 & * \end{pmatrix} \right\}$$

Then an ideal is \underline{m} -full if it is stable under the action of this group.

Proof. Call the group above G . It is easy to see that a G -stable ideal is characterized by saying that (1) it is generated by monomials in x_n , and (2) is closed under the Euler derivations, $x_i \partial / \partial x_n$, $i = 1, 2, \dots, n-1$. Here a monomial in x_n means an element of the form $f' x_n^e$, where $f' \in R' := k[x_1, x_2, \dots, x_{n-1}]$, and e an integer. By (1) we assume \underline{a} is generated by $h_i = h'_i x_n^{e_i}$, $i = 1, 2, \dots, m$, $h'_i \in R'$. Then \underline{ma} is generated by $x_j h_i$, $j = 1, 2, \dots, n$,

$i = 1, 2, \dots, m$. We want to show that $\underline{ma}:x_n = \underline{a}$. That $\underline{ma}:x_n \supset \underline{a}$ is obvious. Assume $f \in \underline{ma}:x_n$. Then $x_n f \in \underline{ma}$. Since \underline{ma} is also G -stable, we may assume $x_n f$ (hence f) is a monomial in x_n . Write

$$x_n f = \sum A_{ij} x_j h_i = \sum A_{ij} x_j h_i' x_n^{e_i} \dots\dots\dots (*)$$

where $A_{ij} \in R$. We express each A_{ij} as a polynomial in x_n with coefficients in R' , expand the right hand side of (*), and keeping in mind the fact $x_j h_i' x_n^{e_i}$ are all monomials in x_n collect the terms whose x_n -degree is the same as that of $x_n f$. Then it should be equal to $x_n f$, as it is a monomial in x_n . Thus we may assume all A_{ij} in (*) are monomials in x_n . Now we divide the right hand side of (*) by x_n , term by term. Note that if $x_j \neq x_n$ and $e_i = 0$, A_{ij} should be divisible by x_n . Now notice that if $e_i > 0$, then $x_j h_i' x_n^{e_i-1}$ differs from $x_j \partial/\partial x_n h_i$ only by a non-zero constant multiple. By (2) we conclude $f \in \underline{a}$.

DEFINITION 2. Let (R, \underline{m}, k) be a local ring with $\text{emb.dim } R = n$. We define the "completely \underline{m} -full" ideals recursively as follows.

(a) If $\text{emb.dim } R = 0$ (i.e., R is a field), then the 0 ideal is completely \underline{m} -full.

(b) If $\text{emb.dim } R > 0$, then \underline{a} is completely \underline{m} -full if $\underline{am}:z = \underline{a}$ and $\underline{a} + zR/zR$ is completely \underline{m} -full as an ideal of R/zR , where z is a general element. (Since $z \in \underline{m} \setminus \underline{m}^2$, the definition makes sense by induction on $\text{emb.dim } R$.)

EXAMPLE 3. Let R be as in Example 1. Let B be the Borel subgroup of $GL(n)$. I.e.,

$$B = \left\{ \begin{pmatrix} * & * & * & * & \dots & * & * \\ 0 & * & * & * & \dots & * & * \\ 0 & 0 & * & * & \dots & * & * \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & \dots & 0 & * \end{pmatrix} \right\}.$$

Let B act on R in the same way as in Example 1. Then any Borel stable ideal is completely \underline{m} -full. (This should be clear in view of Example 1.)

We use μ , τ , ℓ to denote, respectively, the minimal number of generators, the type and the length. Let \underline{a} be an \underline{m} -primary ideal of a local ring (R, \underline{m}, k) . Define $\phi(\underline{a}) = \ell(R/\underline{a} + zR)$ for a general element z . (cf. [10].) Let M be a finite R -module and let b_i be the Betti numbers of M , i.e., $b_i = \dim_k \text{Tor}_i(M, k)$. In this case we write $b_i = b_i(M)$. Note that if \underline{a} is an ideal, then $b_i(\underline{a}) = b_{i+1}(R/\underline{a})$, and $\mu(\underline{a}) = b_0(\underline{a}) = b_1(R/\underline{a})$. Note also that $b_1(\underline{a}) = b_2(R/\underline{a})$ is the number of basic syzygies. If R is a regular local ring of dimension n , then $\tau(\underline{a}) = b_n(R/\underline{a})$.

Let z be a general element of R , and let $\bar{} : R \longrightarrow R/zR$ denote the natural surjection. Then for an ideal \underline{a} of R

the image \bar{a} is the ideal $\underline{a} + zR/zR$ considered as an ideal of R/zR . We have the following result. (For proof see [10] Theorem 2.)

PROPOSITION 4. An \underline{m} -primary ideal \underline{a} is \underline{m} -full if and only if $\mu(\underline{a}) = \phi(\underline{ma}) = \phi(\underline{a}) + \mu(\bar{a})$. (The second equal holds generally.) In this case $\tau(\underline{a}) = \phi(\underline{a})$.

§2. The syzygies of \underline{m} -full ideals

PROPOSITION 5 (Huneke). Let (R, \underline{m}, k) be a local ring and \underline{a} an \underline{m} -full ideal. Let z be a general element of R , and let $\bar{} : R \longrightarrow R = R/zR$ denote the natural map. Then any syzygy of \bar{a} lifts to a syzygy of \underline{a} .

Proof. Write $\underline{a} = (f_1, f_2, \dots, f_r, zf_{r+1}, \dots, zf_s)$, with

$\mu(\bar{a}) = r$ and $\mu(\underline{a}) = s$. Suppose $\sum_{i=1}^r \bar{a}_i \bar{f}_i = 0$. Then $\sum_{i=1}^r a_i f_i =$

zh for some $h \in R$. Observe that $h \in \underline{ma}:z = \underline{a}$. So $h =$

$\sum_{i=1}^r g_i f_i + \sum_{j=r+1}^s g_j (zf_j)$. This gives us the syzygy

$\sum_i (a_i - zg_i) f_i + \sum_j (-zg_j)(zf_j) = 0$, as wanted. Q.E.D.

Temporarily we will call a syzygy obtained this way essential. Namely, an essential syzygy of \underline{a} is a syzygy that reduces to a non-trivial syzygy of $\underline{a} \bmod z$. (We understand that we fix a general element z in the beginning.) Obviously there are at least $b_1(\overline{a})$ such independent syzygies. In the next paragraph we will find another kind of syzygies which we call superficial.

First notice that $\underline{ma}:z=\underline{a}$ implies $\underline{a}:\underline{m}=\underline{a}:z$. In fact $\underline{a}:\underline{m} = (\underline{ma}:z):\underline{m} = (\underline{ma}:\underline{m}):z \supset \underline{a}:z$. Thus $\underline{a}:z = \underline{a}:\underline{m}$, since the other inclusion is obvious. Again assume $\underline{ma}:z = \underline{a}$ with z a general element and write $\underline{a} = (f_1, \dots, f_r, zf_{r+1}, \dots, zf_s)$ as in the proof of Proposition 5. Now suppose x is any element in $\underline{m} \setminus zR$, and j_0 is an integer such that $r+1 \leq j_0 \leq s$. Since $\underline{a}:\underline{m} = \underline{a}:z$, $f_{j_0} \in \underline{a}:\underline{m}$. Hence $xf_{j_0} \in \underline{a}$. So we may write

$$x_{j0}^f = \sum_{i=1}^r a_i f_i + \sum_{j=r+1}^s a_j (z_j^f).$$

Multiply both sides by z . Then $x(zf_{j_0}) =$
 $[(za_i)f_i + [(za_j)(zf_j)]$. This gives us the following syzygy:
 $[-za_1 -za_2 \dots -za_r -za_{r+1} \dots \dots \dots$
 $\dots \dots \dots -za_{j_0-1} \quad x-za_{j_0} \quad -za_{j_0+1} \quad \dots -za_s]$.

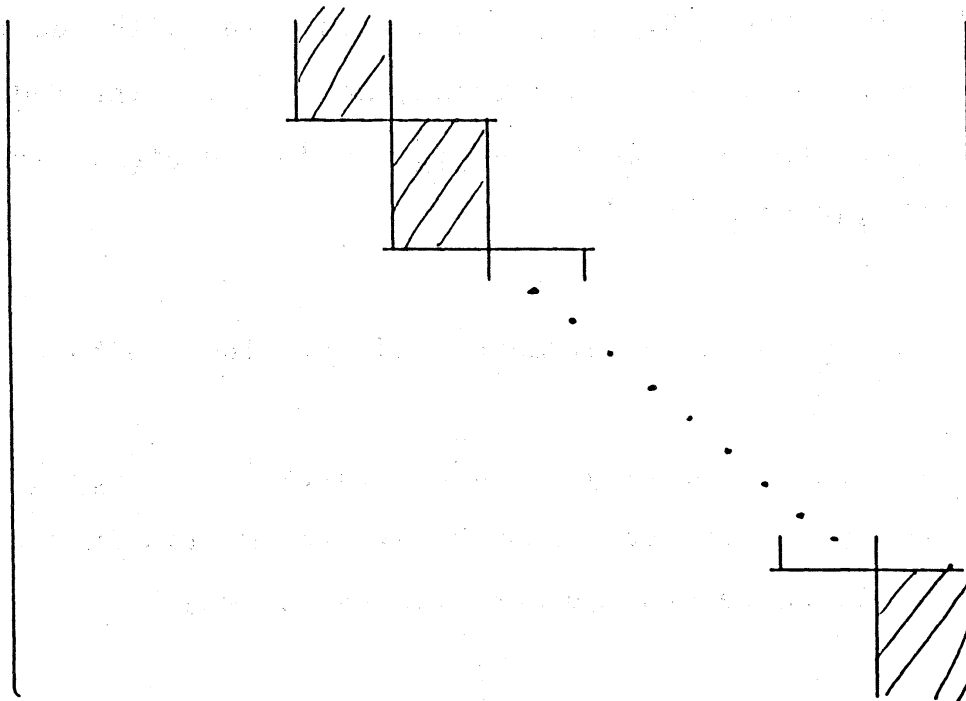
Suppose that $(x_1, x_2, \dots, x_{n-1}, z)$ is a minimal generating set of \underline{m} . For each pair (x_i, zf_j) , $1 \leq i \leq n-1$, $r+1 \leq j \leq s$, we may construct a sygygy in the above described fashion. We will call them superficial syzygies. Obviously


there are $(\mu(\underline{m}) - 1) \times (s-r)$ such syzygies. They are, together with essential syzygies, all independent, since they are independent modulo z . We claim that we have obtained all basic syzygies of \underline{a} , provided that z is a non-zero-divisor. In fact we prove

THEOREM 6. Let (R, \underline{m}, k) be a local ring with depth $R > 0$. Suppose that \underline{a} is an ideal of R such that $\underline{ma}:z=\underline{a}$ for a general element z . Let $r = \mu(\overline{a})$ and $s = \mu(\underline{a})$. Then $b_1(\underline{a}) = b_1(\overline{a}) + (\mu(\underline{m})-1) \times (s-r)$. (Recall that b_1 of an ideal is the minimal number of basic syzygies.)

Proof. Since z is a general element and since depth $R > 0$, z is a non-zero-divisor. Let M be the submodule of R^s generated by all the syzygies, both essential and superficial, described above. Assume, contrary to the assertion, $b_1(\underline{a}) > b_1(\overline{a}) + (\mu(\underline{m})-1) \times (s-r)$. This means that there is a basic syzygy of \underline{a} which is not in M . Say $A = [a_1 \dots a_s]$ is such a syzygy. Then this will be a basic syzygy even after any element of M is added to it. Let \underline{M} be the matrix consisting of the generators of M . Then $\underline{M} \bmod z$ looks like this.

$$\left[\begin{array}{c|c} \underline{\underline{SYZ}}(\overline{a}) & \\ \hline & \text{///} \end{array} \right]$$



where $\underline{\underline{\text{SYZ}}}(\underline{\underline{a}})$ is a syzygy matrix of $\underline{\underline{a}}$ (in the obvious sense), and each block  is the transpose of $[\bar{x}_1 \ \bar{x}_2 \ \dots \ \bar{x}_{n-1}]$. Now by adding elements of M to A , we may assume that all a_i are in zR for $i \geq r+1$, since every one of them is in $(x_1, x_2, \dots, x_{n-1}) \bmod z$. Then A is an essential syzygy. But all essential syzygies are already in $M \bmod z$. Thus we conclude that $A + M$ contains an element whose entries are all multiples of z . This is a contradiction since z is a non-zero-divisor and any element in $A + M$ is basic. Q.E.D.

Remark. (i) Note that $s-r = 0$ if $\text{depth } R/\underline{a} > 0$.

(ii) Suppose that \underline{a} is \underline{m} -primary. Then $s-r = \phi(\underline{a})$ by Proposition 4.

COROLLARY 7. Let (R, \underline{m}, k) be a local ring with $\text{depth } R > 0$. Suppose that \underline{a} is an \underline{m} -full ideal, and $\bar{\underline{a}}$ is the reduction by a general element. Put $r = \mu(\bar{\underline{a}})$ and $s = \mu(\underline{a})$. Then $\underline{a} \otimes R/zR \cong \bar{\underline{a}} \oplus (R/\underline{m})^{(s-r)}$.

Proof. Let \underline{M} be a syzygy matrix of \underline{a} . Then we have

the exact sequence $(R/zR)^{s'} \xrightarrow{\bar{\underline{M}}} (R/zR)^s \longrightarrow \underline{a}/z\underline{a} \longrightarrow 0$. Since $\bar{\underline{M}} = \underline{M} \otimes R/zR$ is isomorphic to the matrix in the proof of Theorem 6, we get the isomorphism as asserted.

COROLLARY 8. Let (R, \underline{m}, k) a regular local ring with $n = \mu(\underline{m})$. Let \underline{a} be an \underline{m} -full ideal and $\bar{\underline{a}}$ the reduction by a general element and $r = \mu(\bar{\underline{a}})$, $s = \mu(\underline{a})$ as above. Then

$$b_i(R/\underline{a}) = b_i(\bar{R}/\bar{\underline{a}}) + \binom{n-1}{i-1} \times (s-r).$$

Proof. Put $b_i = b_i(R/\underline{a})$. Then we have a minimal free resolution:

$$0 \longrightarrow R^{b_n} \longrightarrow R^{b_{n-1}} \longrightarrow \dots \longrightarrow R^{b_2} \longrightarrow R^{b_1} \longrightarrow \underline{a}.$$

Since $\text{depth}(R/\underline{a}) \geq 1$ and since $\text{pd}_R(R/zR) = 1$, we get a minimal free resolution of $\underline{a}/z\underline{a}$ by applying the tensor product $\otimes R/zR$ to it. Since a minimal free resolution of $\bar{R}/(\bar{x}_1, \bar{x}_2, \dots, \bar{x}_{n-1})$ over \bar{R} is given by the exterior algebra on the generators of $\bar{\underline{m}}$, the assertion follows immediately.

COROLLARY 9. Let (R, \underline{m}, k) be a regular local ring of dimension n . Let \underline{a} be a completely \underline{m} -full ideal. Let z_1, \dots, z_n be a set of generators of \underline{m} consisting of general elements. (cf. §1.) Set

$$R^{(0)} = R,$$

$$R^{(i)} = R/(z_n, z_{n-1}, \dots, z_{n-i+1})R, \quad i = 1, \dots, n,$$

$$\ell_i = \mu(\underline{a}R^{(i-1)}) - \mu(\underline{a}R^{(i)}), \quad i = 1, \dots, n.$$

$$\text{Then } b_i(R/\underline{a}) = \binom{n-1}{i-1} \ell_1 + \binom{n-2}{i-1} \ell_2 + \dots + \binom{1}{i-1} \ell_{n-1} + \binom{0}{i-1} \ell_n.$$

$$\text{Here } \binom{p}{q} = \frac{p!}{(p-q)!q!} \text{ for } 0 \leq q \leq p, \text{ and } \binom{p}{q} = 0$$

otherwise.

Proof. Immediate by induction.

Remark. In the corollary above, if \underline{a} is \underline{m} -primary, then

$$\ell_i = \ell(R/\underline{a} + (z_n, z_{n-1}, \dots, z_{n-i+1})). \quad (\text{See Proposition 4.})$$

DEFINITION 10. Let (R, \underline{m}, k) be a regular local ring.

For an \underline{m} -primary ideal \underline{a} , we define $B_i(R/\underline{a})$ to be the right hand side of Corollary 9, with $\ell_i =$

$\ell(R/\underline{a} + (z_n, \dots, z_{n-i+1}))$. In particular the same definition is used for \underline{m} -primary homogeneous ideals in a polynomial ring.

THEOREM 11. Let R be a polynomial ring over a field of

characteristic 0. Let \underline{a} be a homogeneous \underline{m} -primary ideal. Then $b_i(R/\underline{a}) \leq B_i(R/\underline{a})$ for all i .

Proof. We need the theory of Gröbner bases. The reader unfamiliar with it is referred to [3], [4] and [8]. We confine ourselves with the outline of proof. First fix a set of generic variables z_1, z_2, \dots, z_n , and the graduated reverse lexicographic order on the set of monomials with $z_1 > z_2 > \dots > z_n$. For $f \in R$ we denote by $\text{in}(f)$ the initial monomial of f , and for an ideal \underline{a} we denote by $\text{in}(\underline{a})$ the ideal generated by all the monomials $\text{in}(f)$, $f \in \underline{a}$. We say that $g_1, g_2, \dots, g_s \in \underline{a}$ are a Gröbner basis of \underline{a} if $\text{in}(g_1), \dots, \text{in}(g_s)$ generate $\text{in}(\underline{a})$. It is known that $\text{in}(\underline{a})$ is Borel stable, hence completely \underline{m} -full. (See for example [2] Proposition 1.) It is easy to see that if (g_1, \dots, g_s) is a Gröbner basis of \underline{a} then (g_1, \dots, g_s, z_n) is a Gröbner basis of $\underline{a} + zR$. (Here we need to use the reverse lexicographic order. See [1] Lemma 2.2.) Hence $B_i(R/\underline{a}) = B_i(R/\text{in}(\underline{a}))$. Now by the general theory of Gröbner bases, a set of basic syzygis of \underline{a} is obtained through the reduction process of syzygies (including higher syzygies) of initial monomials of its Gröbner basis. Therefore b_i does not exceed B_i for any i . For details see [8] Lemma 7.6 on p.157.

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